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(54) **ANGLE MEASUREMENT SYSTEM INCLUDING MAGNET WITH SUBSTANTIALLY SQUARE FACE FOR THROUGH-SHAFT APPLICATIONS**

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G01B 7/30 (2006.01)

(52) **U.S. Cl.**
USPC **324/207.25**; 324/207.21

(58) **Field of Classification Search**
USPC 324/207.25
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,811,968	A *	9/1998	Nakazawa et al.	324/207.2
6,191,579	B1	2/2001	Striker	
6,489,761	B1	12/2002	Schroeder et al.	
7,358,724	B2	4/2008	Taylor et al.	
7,382,120	B2	6/2008	Narasimhan et al.	
7,420,363	B2	9/2008	Hatanaka et al.	
7,808,234	B2	10/2010	Kurihara	
2005/0068024	A1	3/2005	Byram	
2008/0116884	A1	5/2008	Rettig et al.	
2008/0218158	A1 *	9/2008	Carlson et al.	324/207.2
2010/0315074	A1	12/2010	Abe et al.	
2011/0025309	A1	2/2011	Saruki et al.	
2011/0121824	A1 *	5/2011	Sterling	324/207.22

FOREIGN PATENT DOCUMENTS

WO	2004113928	A2	12/2004

* cited by examiner

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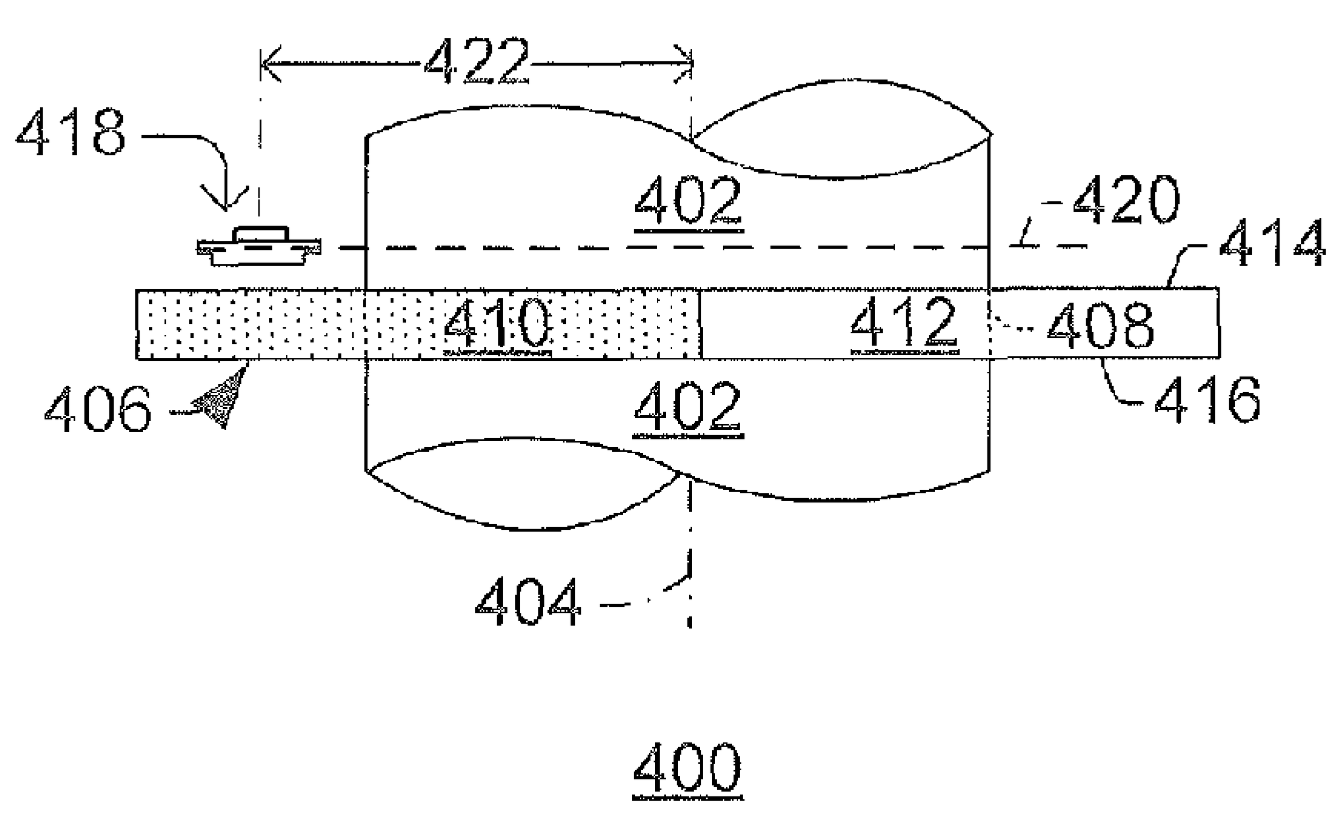
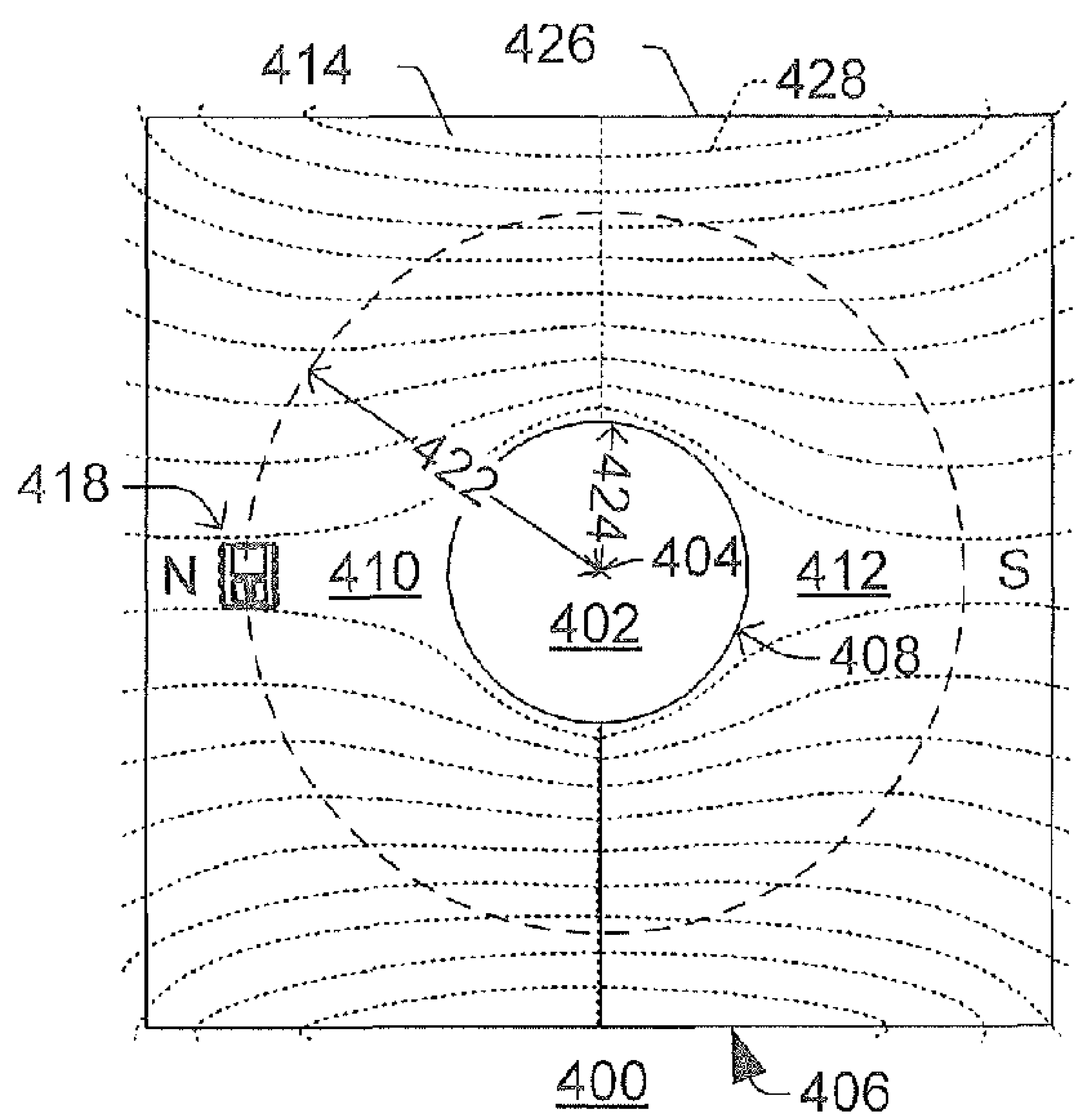
(57) **ABSTRACT**

To make the magnetic field lines straighter and more parallel to one another, the present disclosure makes use of substantially square magnets with through-holes therein. It will be appreciated that "substantially square" magnets include magnets that are precisely square as well as magnets that are approximately square (e.g., have rounded corners or other small deviations from being square.) By providing straighter and more parallel magnetic field lines, such substantially square magnets tend to enable greater precision and accuracy when rotational angles of a shaft are measured.

18 Claims, 5 Drawing Sheets





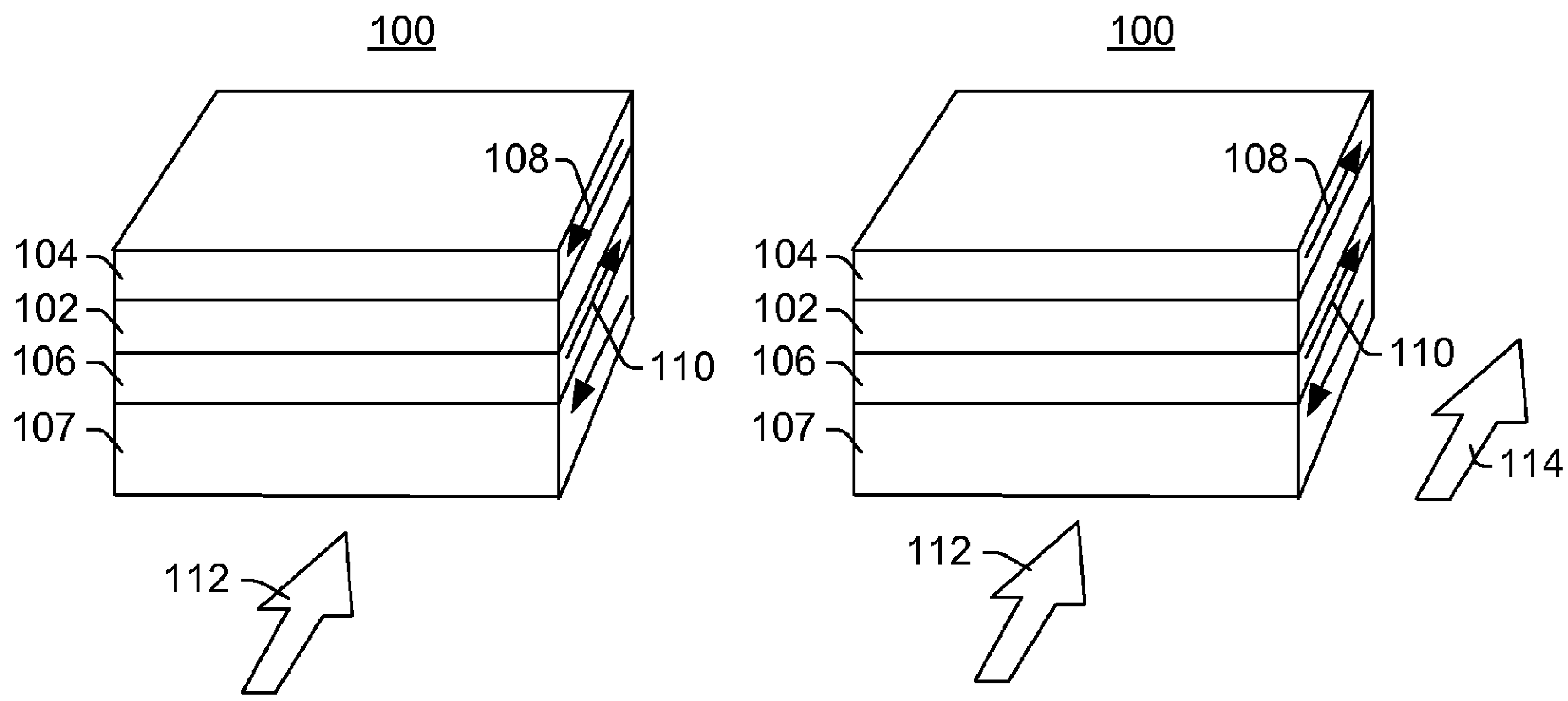


FIG. 1A
(PRIOR ART)

FIG. 1B
(PRIOR ART)

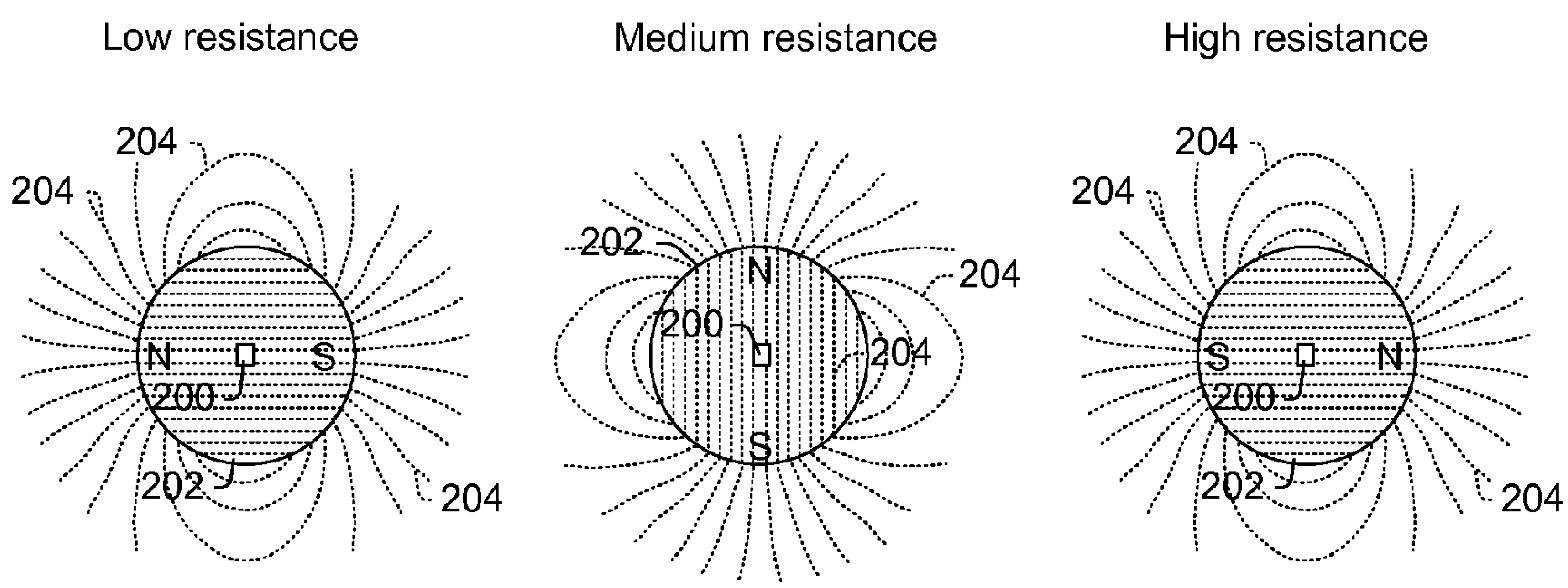


FIG. 2A
(PRIOR ART)

FIG. 2B
(PRIOR ART)

FIG. 2C
(PRIOR ART)

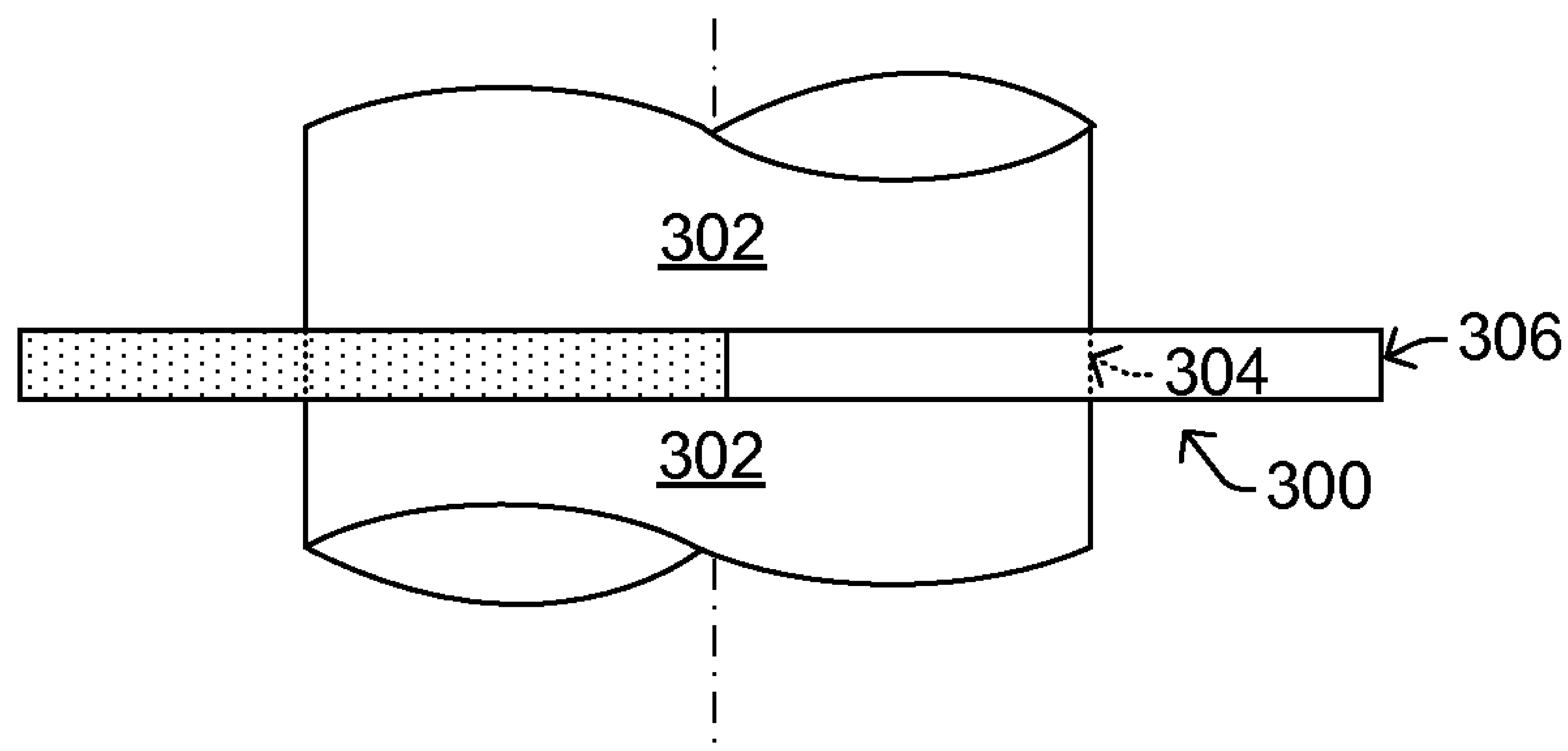


FIG. 3A
(PRIOR ART)

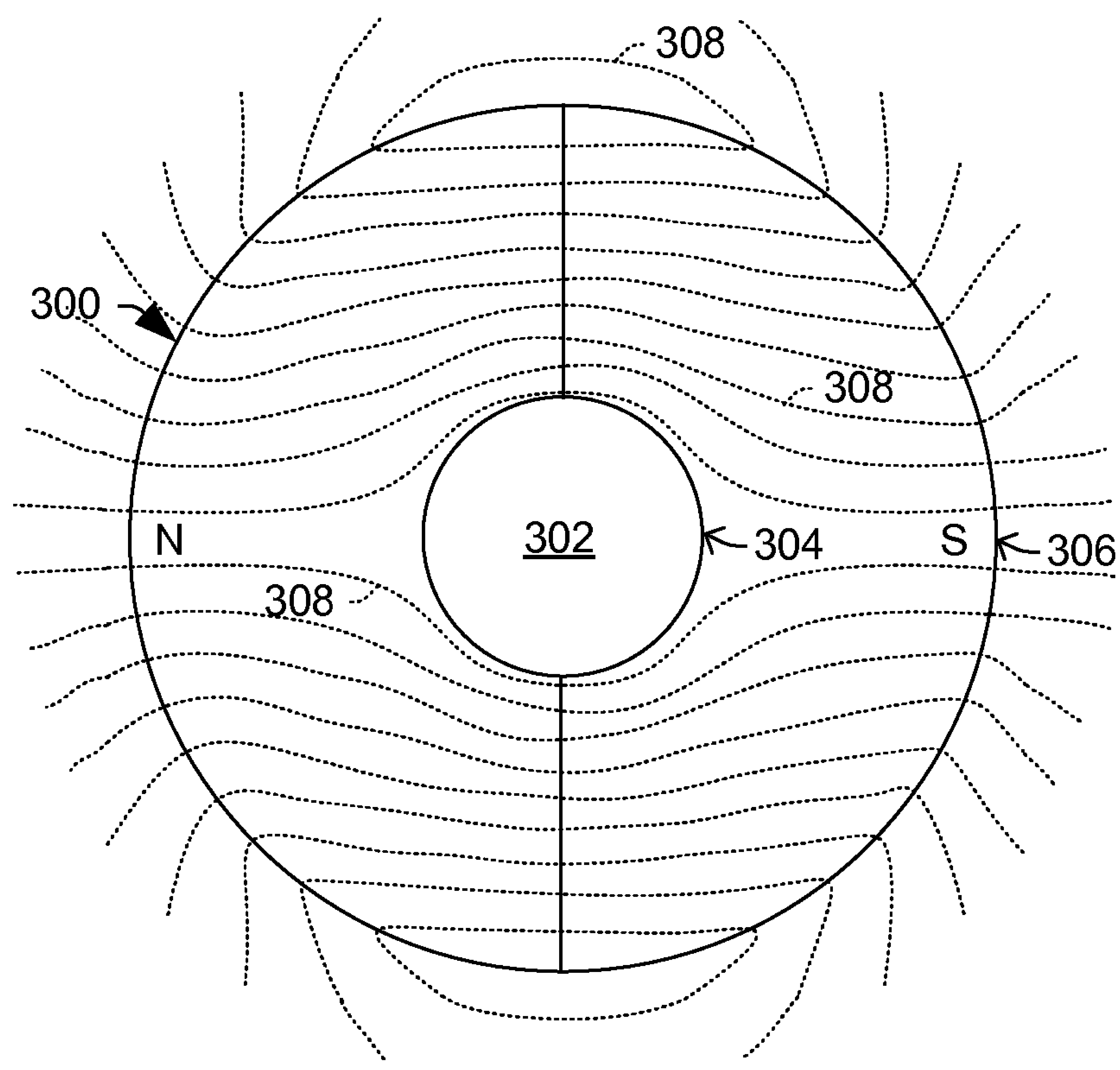


FIG. 3B
(PRIOR ART)

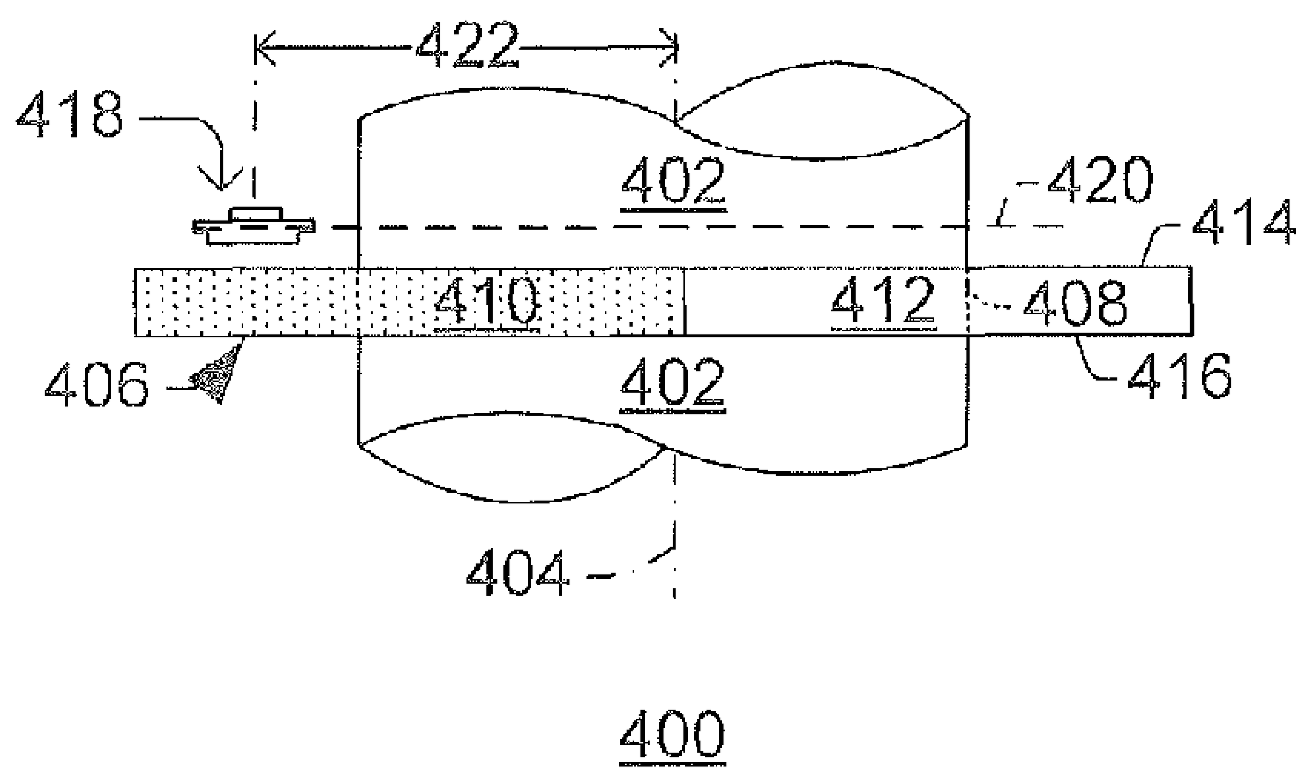


FIG. 4A

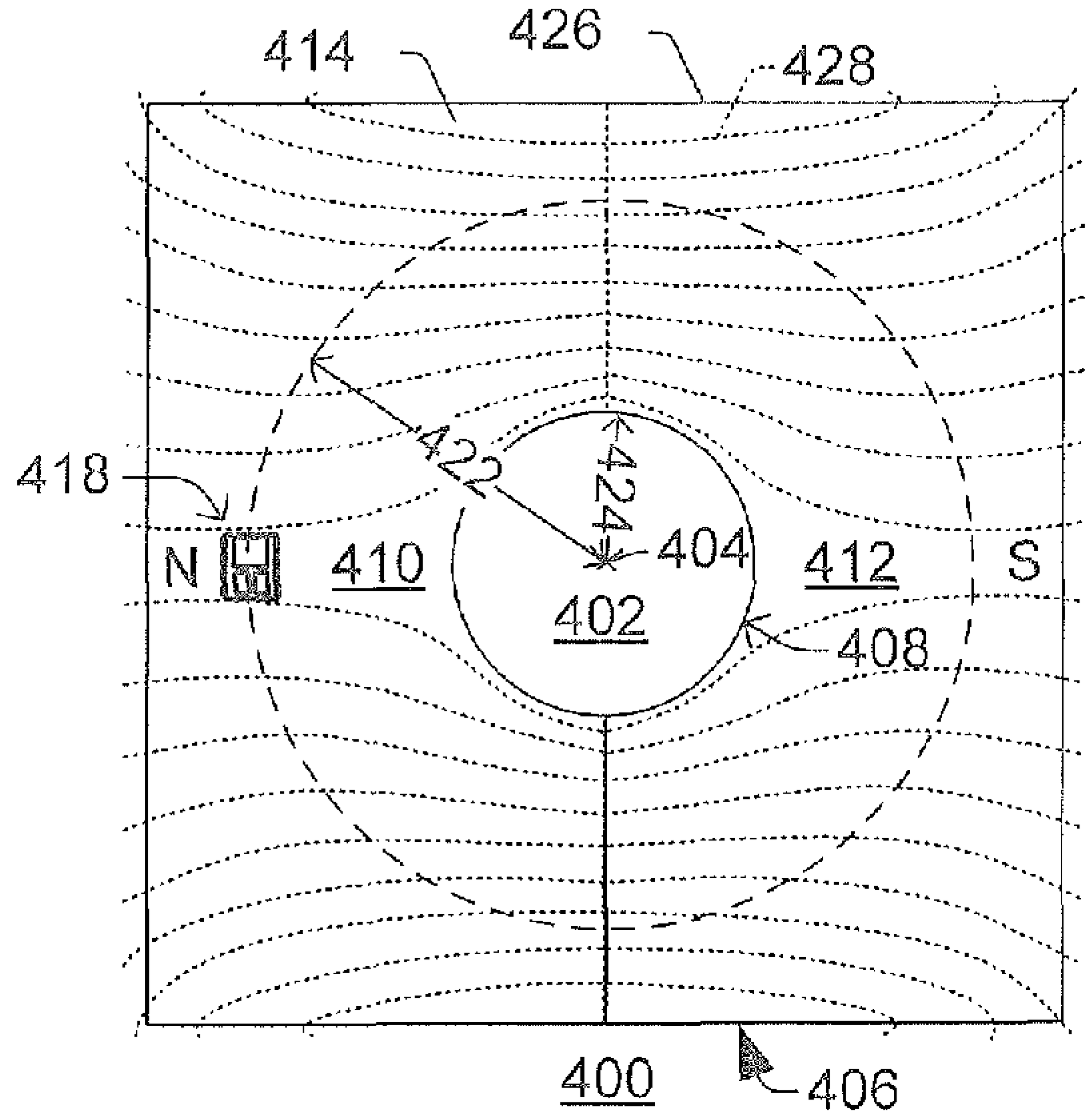


FIG. 4B

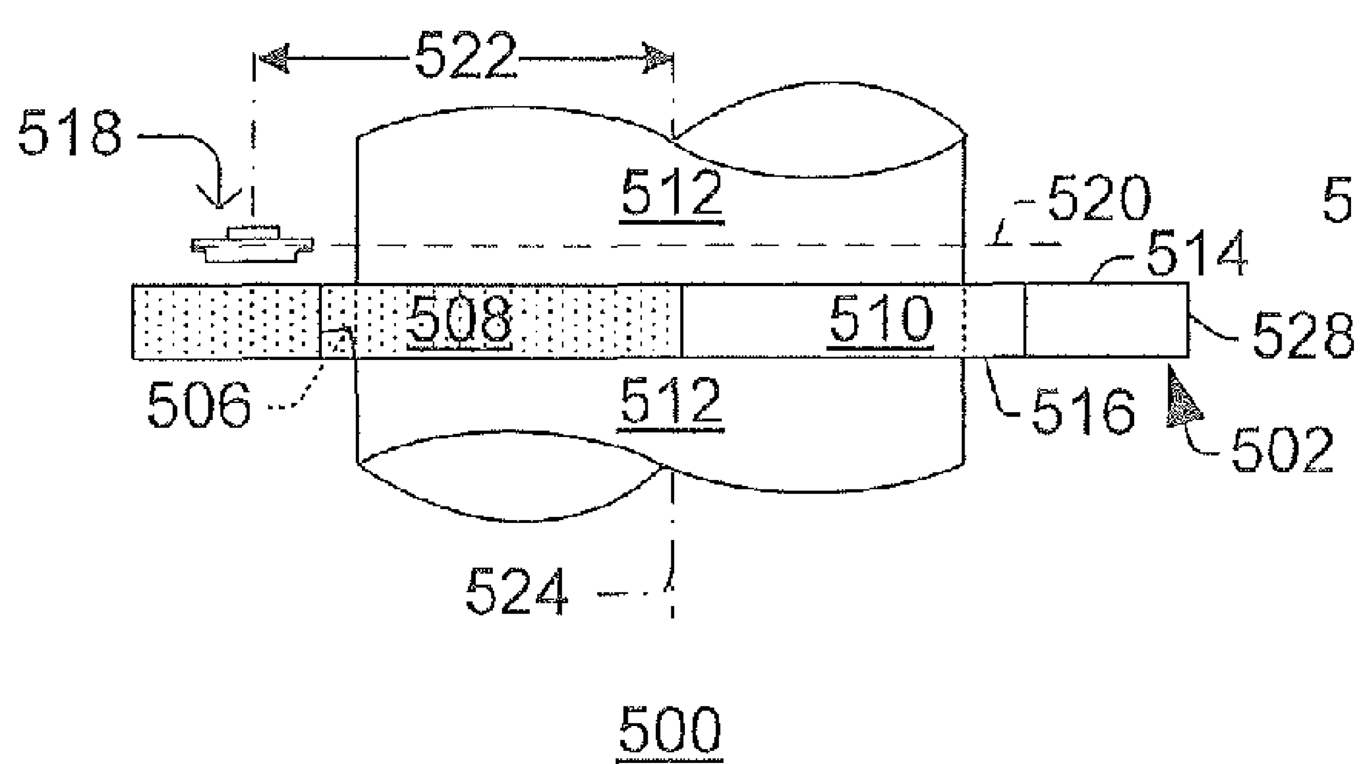


FIG. 5A

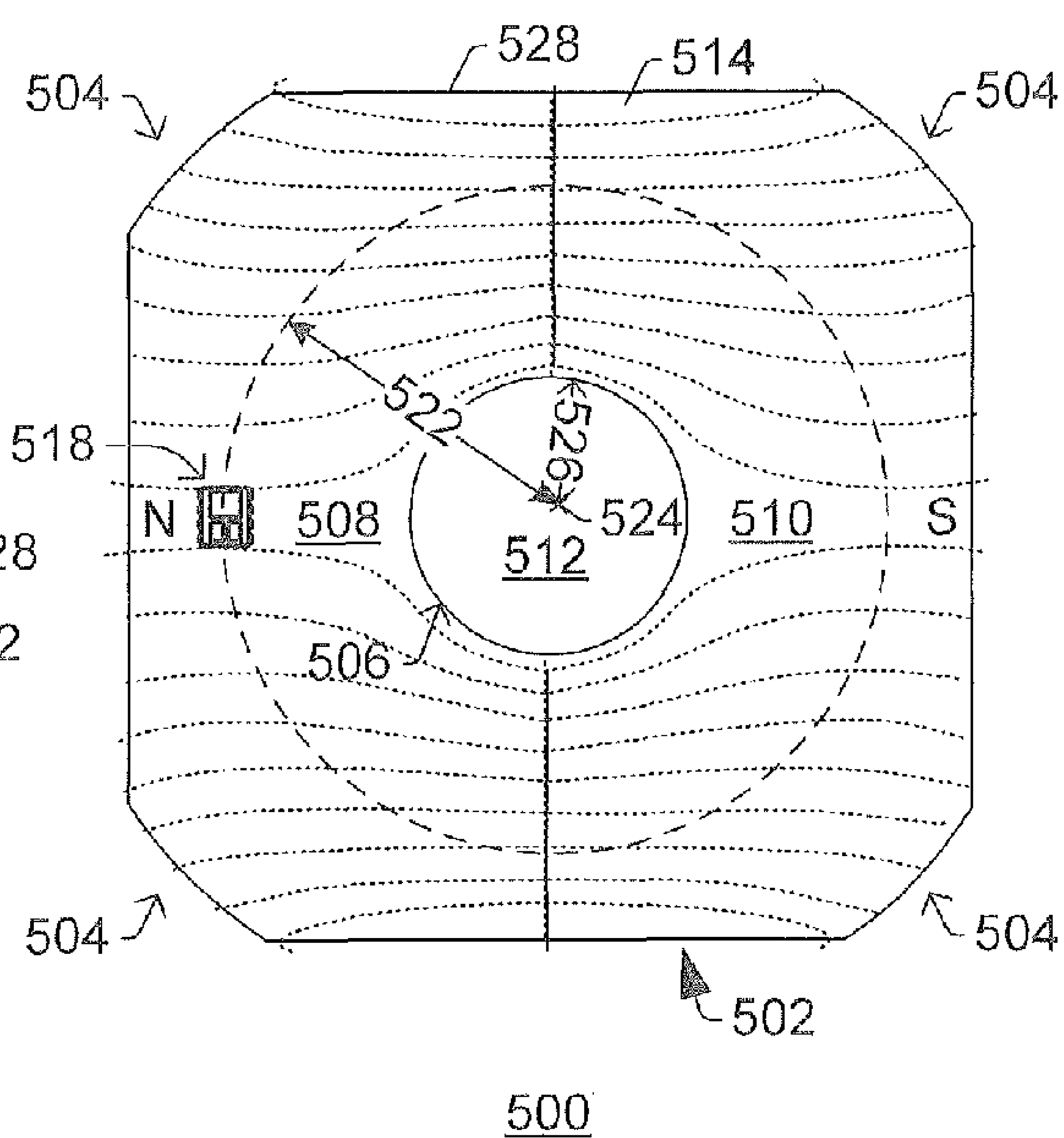


FIG. 5B

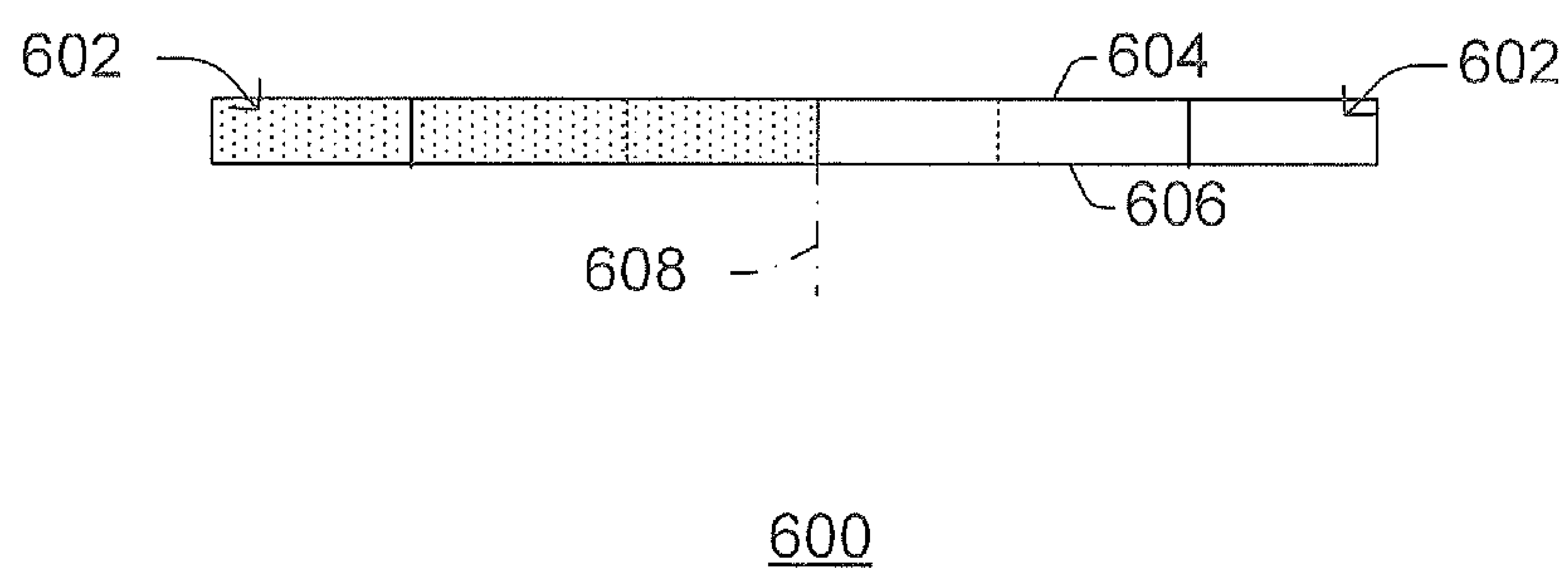

602
604
602
606
608
600

FIG. 6A

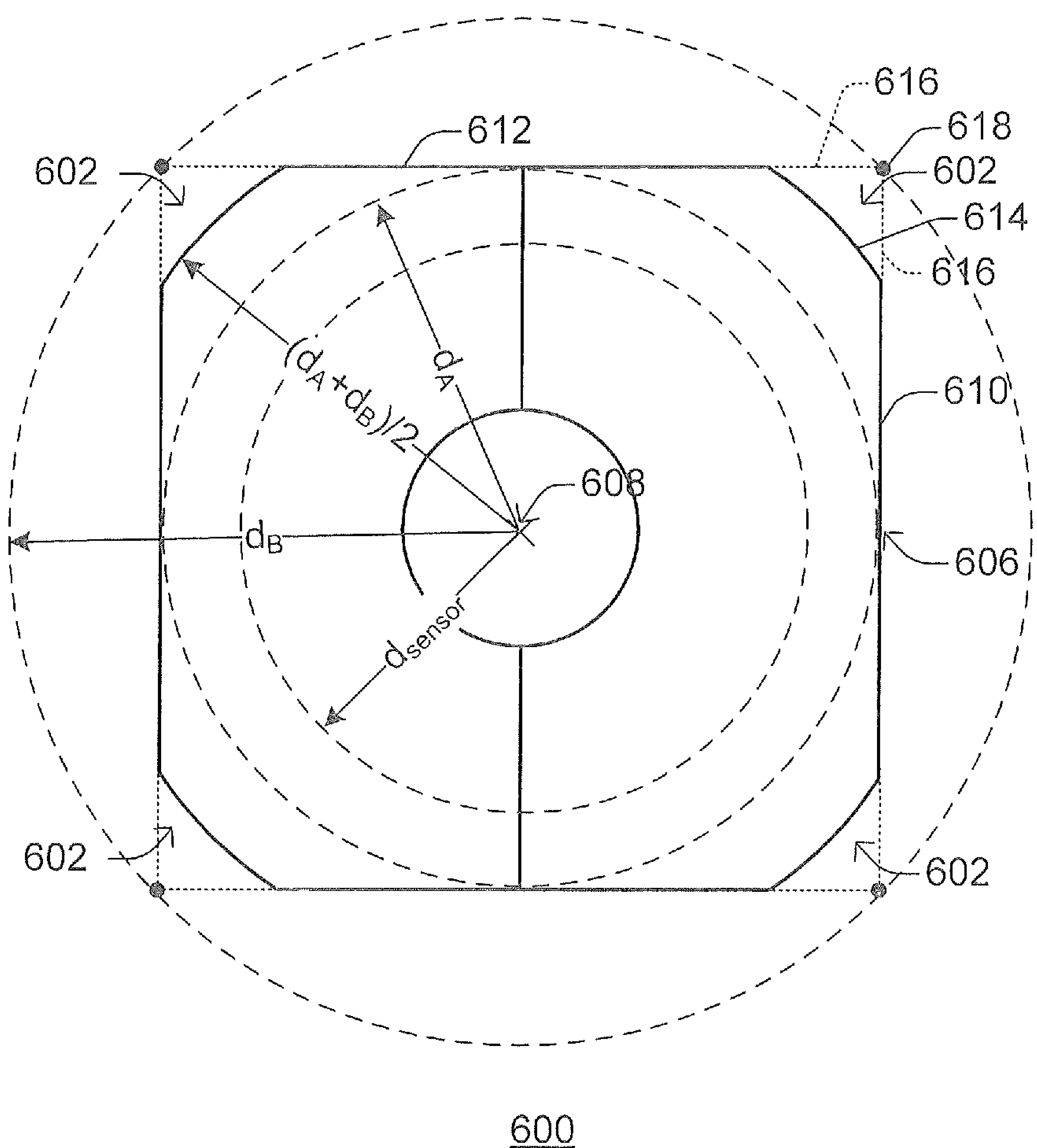

616
618
612
602
602
614
616
$(d_A+d_B)/2$
d_A
610
608
d_B
606
d_{sensor}
602
602
600

FIG. 6B

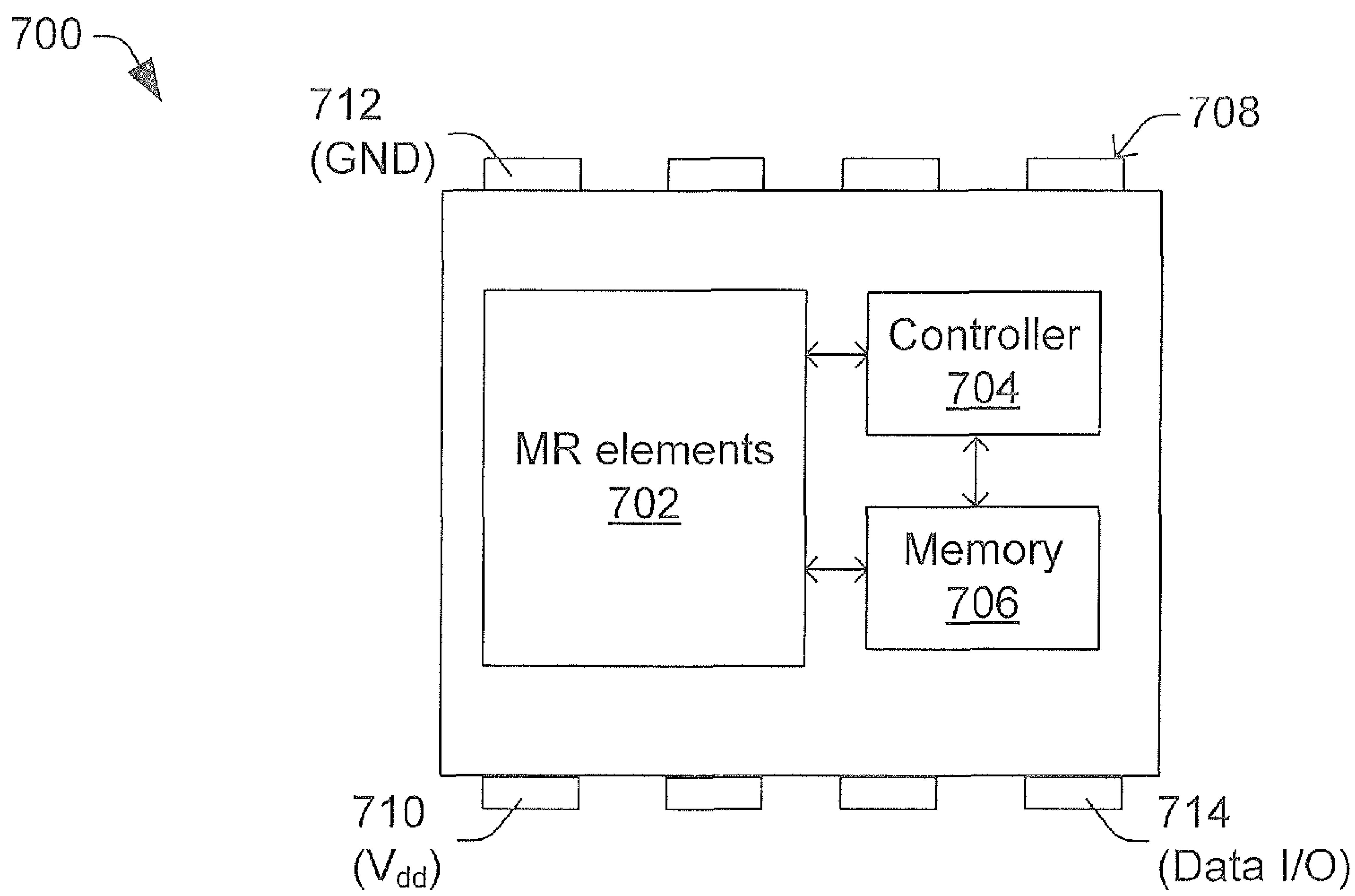

700
712
(GND)
708
Controller
704
MR elements
702
Memory
706
710
(Vdd)
714
(Data I/O)

FIG. 7

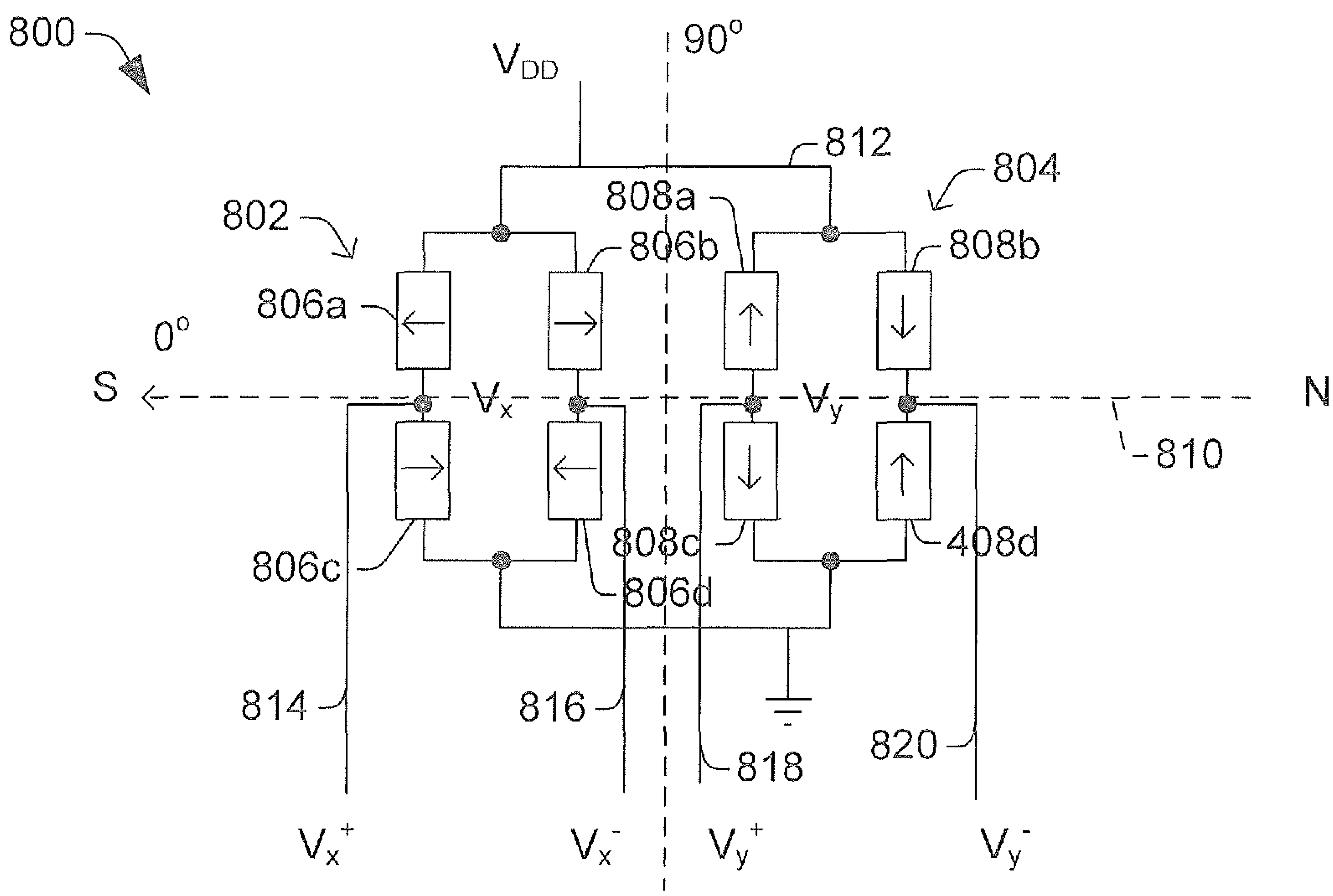

800
VDD
90°
812
804
802
808a
806b
808b
806a
0°
S
Vx
Vy
N
810
806c
808c
806d
408d
814
816
818
820
Vx+
Vx-
Vy+
Vy-

FIG. 8

ANGLE MEASUREMENT SYSTEM INCLUDING MAGNET WITH SUBSTANTIALLY SQUARE FACE FOR THROUGH-SHAFT APPLICATIONS

BACKGROUND

Magnetic field directional sensors, such as Giant Magneto Resistive (GMR) or Anisotropic Magneto Resistive (AMR) sensors, for example, are used in a wide variety of applications. FIGS. **1A-1B** show a how a magnetic field directional sensor **100** (e.g., GMR sensor) behaves under different magnetic fields. The magnetic field directional sensor **100** includes a nonmagnetic conducting middle layer **102** (e.g., an ultrathin copper layer) sandwiched between first and second ferromagnetic alloy layers **104**, **106**. An artificial anti-ferromagnetic layer **107** is disposed under the second ferromagnetic allow layer **106**. Additional layers can also be included. As will be appreciated in more detail below, the resistance of the magnetic field directional sensor **100** varies depending on the magnitude and direction of a magnetic field applied to the sensor **100**.

FIG. **1A** shows a condition where no external magnetic field is applied to the sensor **100**. Under this condition, the magnetic moments of the first and second alloy layers **104**, **106** face opposite directions (see arrows **108**, **110**) due to anti-ferromagnetic coupling, and the current **112** attempting to pass through the sensor **100** encounters a large resistance.

In contrast, in FIG. **1B** an external magnetic field as shown by arrow **114** has been applied to overcome anti-ferromagnetic coupling. Within the first and second alloy layers **104**, **106**; this magnetic field **114** tends to align the magnetic moments, as shown by arrows **116**, **118**. As a consequence, the current **120** attempting to pass though the sensor **100** in FIG. **1B** encounters a low resistance, relative to FIG. **1A**. Thus, by monitoring the resistance of the sensor **100**, the magnitude and/or direction of a magnetic field (e.g., **114**) can be evaluated.

One particular application of interest for GMR/AMR sensors is determining an angular position of a rotating shaft. In conventional solutions, a permanent magnet, sometimes referred to as a "button" magnet, can be mounted to an end of a rotating shaft so as to be centered on the shaft's axis of rotation. FIGS. **2A-2C** show top views of such a button magnet **202** as it rotates, wherein a magnetic field directional sensor **200** (e.g., GMR or AMR) is positioned there over so as to remain stationary as the button magnet **202** rotates there under. Within the confines of the button magnet **202**, magnetic field lines **204** are straight and parallel to one another. As the shaft (and hence button magnet **202**) rotate, the directionality of the magnetic field lines **204** passing though the sensor **200** change accordingly. For example, in FIG. **2A** (e.g., a 0° angular position) the magnetic field lines **204** tend to align the magnetic moments of layers in the sensor **200**, thereby creating a low resistance state in the sensor **200**. However, as the magnetic field lines **204** rotate (FIG. **2B**—a 90° angular position, FIG. **2C**—a 180° angular position) they no longer align the magnetic moments as strongly, and the resistance of the sensor **200** can increase proportionately. Because the resistance of the sensor **200** changes depending on the directionality of the magnetic field lines **204** passing there though, a controller (not shown) can measure the resistance of the sensor **200** over time and continuously correlate the resistance at any given time to a corresponding magnetic field direction. In this way, the controller can determine the rotational angle of the shaft as the shaft rotates. In other cases the angle calculation is completed by an intelligent state machine and firmware included in the sensor's manufacturing process. How the angle is ultimately calculated is dependent on the level of sensor integration.

Unfortunately, in many applications, it isn't feasible to mount a circular button magnet on an end of a rotating shaft, for example, due to space concerns or due to some other component needing to be mounted to the end of the shaft. For example, in vehicles, both ends of an electric drive motor shaft may be used to drive two independent systems leaving no access at the shaft ends for a magnet and sensor.

Therefore, improved angle sensing techniques are needed wherein angle sensors are disposed along the length of a shaft, rather than at an end of the shaft.

DRAWINGS

FIGS. **1A-1B** are isometric diagrams depicting how one example of how a magnetic field directionality sensor can operate.

FIGS. **2A-2C** are top views of a conventional button magnet mounted atop a rotating shaft.

FIGS. **3A-3B** are side and top views, respectively, of a ring magnet mounted radially about a rotatable shaft that suffers from some shortcomings.

FIGS. **4A-4B** are side and top views, respectively, of a square magnet mounted about a rotatable shaft in accordance with some embodiments.

FIGS. **5A-5B** are side and top views, respectively, of a square magnet with rounded corners mounted about a rotatable shaft in accordance with some embodiments.

FIG. **6A-6B** are side and top views of a square magnet with rounded corners in accordance with some embodiments.

FIG. **7** is a block diagram illustrating one embodiment of a GMR or AMR angle sensor in accordance with some embodiments.

FIG. **8** is a block diagram illustrating one embodiment of a GMR sensing array in accordance with some embodiments.

DETAILED DESCRIPTION

The claimed subject matter is now described with reference to the drawings, where like reference numerals are used to refer to like elements throughout. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the claimed subject matter. It may be evident, however, that the claimed subject matter may be practiced without these specific details.

Aspects of the present disclosure relate to techniques for measuring an angular position of a rotating shaft. As will be described in greater detail below, some embodiments of the present disclosure include a magnet mounted radially or peripherally about the axial length of a shaft. The magnet includes first and second face surfaces, each of which is substantially square. It will be appreciated that "substantially square" in the context of this disclosure can mean actually square or approximately square (e.g., square with rounded corners). By including substantially square magnets with through-holes for rotating shaft applications, more accurate angle measurements can be taken relative to previous implementations.

FIGS. **3A-3B** show a side view and top view, respectively, of a ring magnet **300** that is mounted radially about a rotatable shaft **302** and which suffers from some shortcomings. Compared to the button magnet shown in FIG. **2**, this ring magnet **300** is advantageous in that it includes a through-hole **304** so it can be mounted about the axial length of the shaft **302**. Also, because the ring magnet **300** has a continuous, circular edge **306**, it is relatively straightforward to manufacture and exhibits good balance (e.g., limited "wobble") as the shaft **302** rotates. Unfortunately, however, unlike conventional button magnets (e.g., button magnet **202** in FIG. **2**) which provided straight and parallel magnetic field lines, magnetic field lines **308** in the ring magnet **300** are no longer straight and parallel to one another, due to the through hole **304** in the center of the magnet **300**. These "crooked" field lines **308** make accurate angle measurement more difficult, further exacerbated with sensor positions offset from center, than compared with that of conventional button magnets. Thus, FIG. **3**'s ring magnet **300** is less than ideal for many applications.

To make magnetic field lines more straight and parallel to one another, the present disclosure makes use of substantially square magnets with through-holes therein. It will be appreciated that "substantially square" magnets include magnets that are precisely square as well as magnets that are approximately square (e.g., have rounded corners or other small deviations from being square.) In addition, although through-holes in many instances are circular to accommodate a circular shaft, through-holes can in general have any other shape, such as square, for example. By providing straighter and more parallel magnetic field lines, such substantially square magnets tend to enable greater precision and accuracy when rotational angles of a shaft are measured.

FIGS. **4**A-**4**B illustrate a side view and top view, respectively, of an angle measurement system **400** that includes a square magnet **406**. The angle measurement system **400** is configured to determine an angle of a rotating shaft **402**, which extends along a shaft axis **404**. The square magnet **406**, which includes a through-hole **408** centrally disposed through a north pole region **410** and a south pole region **412**, is fixedly mounted to the shaft **402**. The square magnet **406** includes first and second face surfaces **414**, **416**, respectively. The first and second face surfaces **414**, **416** include first and second apertures, respectively, which define the extents of the through-hole **408** through which the shaft **402** passes.

An angle sensor **418** is configured to measure a time-varying magnetic field produced by the square magnet **406** as the shaft **402** rotates about its axis **404**. In many embodiments, the angle sensor **418** comprises a semiconductor chip having one or more resistor (e.g., GMR or AMR resistor) regions. The angle sensor **418** is often positioned in a plane **420** parallel to the first and/or second face surface (**416**, **418**) such that the resistor region is substantially centered along a constant radius **422** extending from the shaft axis **404**. The angle sensor **418** is often positioned on the plane **420** between an inner radius **424** and an outer perimeter **426** of square magnet **406**.

Compared to the round edge **306** of ring magnet **300** of FIG. **3**, the square face surfaces **414**, **416** of the magnet **406** help to "straighten" and parallelize the magnetic field lines **428** somewhat. Because of this, the square magnet **406** facilitates more precise angular rotation measurement than the ring magnet **300** of FIG. **3**.

FIGS. **5**A-**5**B illustrate a side view and top view, respectively, of another embodiment of an angle measurement system **500**. Rather than including first and second face surfaces that are actually square as depicted in the embodiment of FIGS. **4**A-**4**B, the angle sensor **500** includes a substantially square magnet **502** with rounded corners **504**. These rounded corners **504** can help to further parallelize the magnetic field lines compared to previously discussed implementations, thereby facilitating more accurate angle measurements.

Substantially square magnet **502**, which includes a through-hole **506** centrally disposed through a north pole region **508** and a south pole region **510**, is fixedly mounted to a shaft **512**. The substantially square magnet **502** includes first and second face surfaces **514**, **516**, respectively. The first and second face surfaces **514**, **516** have rounded corners **504** and include first and second apertures, respectively, which define the extents of the through-hole **506** through which the shaft **512** passes.

An angle sensor **518** is configured to measure a time-varying magnetic field produced by the substantially square magnet **502** as the shaft **512** rotates about its axis **524**. In many embodiments, the angle sensor **518** comprises a semiconductor chip having one or more resistor (e.g., GMR or AMR resistor) regions. The angle sensor **518** is often positioned in a plane **520** parallel to the first and/or second face surface (**514**, **516**) such that the resistor region is substantially centered along a constant radius **522** extending from the shaft axis **524**. On this plane **520**, the angle sensor **518** is often positioned between an inner radius **526** and an outer edge **528** of substantially square magnet **502**.

FIGS. **6**A-**6**B show a side view and top view, respectively, of another substantially square magnet **600** with rounded corners **602** in accordance with some embodiments. For purposes of clarity, this embodiment does not show a shaft or angle sensor as with previous embodiments, although this substantially square magnet is typically used in conjunction with them (see e.g., FIG. **5**A-**5**B).

The substantially square magnet **600** includes a first face surface **604**, which has a perimeter **606** disposed laterally about a central axis **608** of the magnet. The perimeter **606** includes a first edge **610** spaced apart from the central axis **608** by a first distance d_A, and a second edge **612** perpendicular to the first edge **610** and spaced apart from the central axis **608** by the first distance d_A. A rounded segment **614** lies between the first edge **610** and the second edge **612** and is spaced apart from the central axis **608** by a second (e.g., radial) distance d_B that is greater than the first distance d_A.

The first edge and second edge **610**, **612**, if extended as shown by lines **616**, would meet at an intersection point **618** outside of the first face surface **604**. The intersection point **618** is spaced apart from the central axis **608** by a third distance d_c that is greater than the second distance d_B.

In some embodiments, the second distance d_B is approximately one half of the sum of the first distance plus the third distance (i.e., $d_B=(d_A+d_C)/2$). This geometry for the rounded corers **602** helps to provide straight and parallel magnetic field lines at a distance at which a sensor will be positioned (d_{sensor}).

FIG. **7** is a block diagram illustrating one embodiment of an angle sensor **700** (e.g., angle sensor **418** in FIGS. **4**A-**4**B and/or angle sensor **518** in FIGS. **5**A-**5**B). As illustrated, in addition to a magneto-resistive (MR) region **702**, angle sensor **700** may further include a controller **704** and a memory **706**, with memory **706** storing values for a plurality of MR parameters (e.g., calibration parameters). Angle sensor **700** further includes a plurality of pins **708**, such as a supply voltage (V_{DD}) pin **710**, a ground pin **712**, and a data I/O pin **714**.

FIG. **8** is a schematic diagram generally illustrating GMR resistor region **800** (e.g., MR resistor region **702** in FIG. **7**) according to one embodiment. As illustrated, GMR resistor region **800** includes a pair of GMR sensor bridges **802** and **804**, with sensor bridge **802** formed by four GMR resistors **806***a*-**806***d* and sensor bridge **804** formed by four GMR resistors **808***a*-**808***d*. According to the bridge implementation of FIG. **8**, GMR sensor bridges **802** and **804** are disposed orthogonal to one another and are respectively configured to sense an x-component and a y-component of a rotating magnetic field, such as the magnetic field indicated by the dashed lines at **810**.

A supply voltage V_{DD} is applied to a terminal **812** via pin **710** and voltage signals V_X+ and V_X− of GMR sensor bridge **802** are measured at terminals **814** and **816**, and voltage signals V_Y+ and V_Y− of GMR sensor bridge **804** are measured at terminals **818** and **820**. In response to an external magnetic field, such as magnetic field **810**, one or more of the GMR resistors **806***a*-**806***d* and **808***a*-**808***d* change in their electrical resistances, causing changes in voltage signals V_X+ and V_X− at terminals **814** and **816** and voltage signals V_Y+ and V_Y− at terminals **818** and **820** which are representative of an angular position of magnetic field **810** relative to a reference vector (e.g. 0-degrees).

Although various embodiments have been described above, variations of these embodiments are also contemplated as falling within the scope of the present disclosure.

As may be appreciated from the details above, angle measurement techniques in accordance with the present disclosure may be beneficial in any number of applications that make use of a rotating shaft. In some applications, these techniques can be used to measure both relative angles and an absolute angle. In essence, a relative angle is an angular position measured within a single 360° rotation, while an absolute angle is an angular position that can account for more than one 360° rotation. For example, a relative angular position could measure a 45° rotation relative to true vertical (with no indication of how many 360° rotations passed from a previous measurement), while an absolute angular position could indicate two complete 360° rotations plus a 45° rotation relative to some fixed line of reference (e.g., 765° rotation relative to the fixed line of reference). While GMR sensors can be used to measure virtually any angle (e.g., less than 360 degrees or greater than 360 degrees), AMR sensors are generally only capable of measuring angles of 180 degrees or less.

In some embodiments, a substantially square magnet can be manufactured using an injection molding technique, in which a rubber or plastic material is impregnated with magnetizable material. In other embodiments, a substantially square magnet can be coupled to a shaft in other manners (e.g., fasteners or adhesives).

Further, although the previously illustrated embodiments show only one angle sensor over each magnet, additional (redundant) angle sensors can also be scattered in various ways angle sensing systems in accordance with this disclosure. If present, redundant angle sensors can often lie in a single plane (e.g., plane **420** in FIG. **4**) over a substantially square magnet (e.g., **406** in FIG. **4**). However, redundant angle sensors can also be "stacked" over one another in these and other implementations. Whatever the arrangement used, redundant angle sensors may help to facilitate reliable angular sensing for a long period of time. Redundant angle sensors also present an opportunity for accuracy confirmation and data quality; if on the PCB the angle sensors are known to be separated by 180 degrees of rotation (for instance) then at any given time these sensors should always provide data separated by 180 degrees, therefore assuring data quality and system accuracy.

As one skilled in the art will appreciate, different companies can refer to a component by different names. This document does not intend to distinguish between components that differ in name but not function herein. In this document the terms "including" and "comprising" are used in an open ended fashion, and thus should be interpreted to mean "including, but not limited to . . . ." Also, the term "couple" (and variations thereof) is intended to mean either an indirect or direct connection. Thus, if a first element is coupled to a second element, that connection may be a direct connection, or may be an indirect connection via other elements and connections. Although various approximately numeric values are provided herein, these numeric values are merely examples should not be used to limit the scope of the disclosure.

Also, although the disclosure has been shown and described with respect to one or more implementations, equivalent alterations and modifications will occur to others skilled in the art based upon a reading and understanding of this specification and the annexed drawings. For example, although this application makes reference to AMR and/or GMR sensors above, it will be appreciated that other magneto-resistive (MR) sensors are also contemplated as falling within the scope of the present disclosure. For instance, tunneling magnetic resistance (TMR) is another type of magnetoresistive effect that can be used in angle sensors in accordance with some embodiments. Other MR sensors could also be included. The disclosure includes all such modifications and alterations and is limited only by the scope of the following claims. In particular regard to the various functions performed by the above described components (e.g., elements and/or resources), the terms used to describe such components are intended to correspond, unless otherwise indicated, to any component which performs the specified function of the described component (e.g., that is functionally equivalent), even though not structurally equivalent to the disclosed structure which performs the function in the herein illustrated exemplary implementations of the disclosure. In addition, while a particular feature of the disclosure may have been disclosed with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular application. In addition, the articles "a" and "an" as used in this application and the appended claims are to be construed to mean "one or more".

Furthermore, to the extent that the terms "includes", "having", "has", "with", or variants thereof are used in either the detailed description or the claims, such terms are intended to be inclusive in a manner similar to the term "comprising."

What is claimed is:

1. An angle measurement system, comprising:

a shaft extending along a shaft axis and configured to axially rotate thereabout;

a magnet including first and second surfaces which are each substantially square, wherein the first and second surfaces include first and second apertures, respectively, and wherein the first and second apertures define extents of a through-hole in the magnet through which the shaft extends; and

an angle sensor configured to measure a time-varying magnetic field produced by the magnet as the shaft rotates to thereby determine an rotational angle of the shaft, where the angle sensor includes a sensing region that is positioned over the first surface of the magnet between an inner perimeter of the magnet proximate to the shaft and an outer perimeter of the magnet.

2. The angle measurement system of claim **1**, wherein the first and second surfaces are square surfaces with rounded corners.

3. The angle measurement system of claim **2**, further comprising:

an angle sensor configured to measure a time-varying magnetic field produced by the magnet as the shaft rotates to determine an rotational angle of the shaft.

4. The angle measurement system of claim **3**, where the angle sensor is fixed at position that is spaced apart from the shaft axis.

5. The angle measurement system of claim **2**, wherein the first surface has a perimeter disposed laterally about the shaft axis, the perimeter comprising:

a first edge spaced apart from the shaft axis by a first distance;

a second edge perpendicular to the first edge and spaced apart from the shaft axis by the first distance;

a rounded segment between the first edge and the second edge and spaced apart from the shaft axis by a second distance that is greater than the first distance.

6. The angle measurement system of claim **5**, wherein the first edge and second edge, if extended, would meet at an intersection point outside of the first surface, and wherein the intersection point is spaced apart from the shaft axis by a third distance that is greater than the second distance.

7. The angle measurement system of claim **6**, wherein the second distance is approximately one half of the sum of the first distance plus the third distance.

8. The angle measurement system of claim **1**, where the angle sensor comprises:

a semiconductor chip that includes an arrangement Magnetoresistive Resistive sensors arranged to determine magnetic field directionality.

9. The angle measurement sensor of claim **8**, where the semiconductor chip comprises a pair of MR sensor bridges arranged orthogonal to one another.

10. The angle measurement system of claim **1**, wherein the angle sensor comprises:

an ultrathin conducting, non-ferromagnetic layer; and

a pair of ferromagnetic layers sandwiched about opposing sides of the conducting, non-ferromagnetic layer.

11. The angle measurement system of claim **1**, where the shaft is adapted to rotate through an absolute angle of more than three-hundred and sixty degrees about the shaft axis.

12. A system, comprising:

a shaft that extends along a shaft axis;

a magnet having opposing surfaces that that are substantially square with rounded corners, wherein the magnet includes a central aperture through which the shaft passes and by which the magnet is mounted to the shaft; and

an angle sensor positioned to determine a rotational angle of the shaft by measuring a time-varying magnetic field produced by the magnet as the shaft rotates, where the angle sensor includes a sensing region that is positioned over a face of the magnet between an inner perimeter of the magnet proximate to the shaft and an outer perimeter of the magnet.

13. The system of claim **12**, where the shaft is adapted to rotate through an absolute angle of more than three-hundred and sixty degrees about the shaft axis.

14. The system of claim **12**, where the shaft is limited to rotation of 360-degrees or less about the shaft axis.

15. The system of claim **12**, where the angle sensor comprises:

a semiconductor chip that includes an arrangement of Magnetoresistive Resistive (MR) sensors arranged to cooperatively determine magnetic field directionality.

16. The system of claim **15**, where the semiconductor chip comprises a pair of MR sensor bridges arranged orthogonal to one another.

17. The system of claim **12**, wherein the angle sensor comprises:

an ultrathin conducting, non-ferromagnetic layer; and

a pair of ferromagnetic layers sandwiched about opposing sides of the conducting, non-ferromagnetic layer.

18. The system of claim **12**, wherein the face of the magnet has a perimeter disposed laterally about the shaft axis, the perimeter comprising:

a first linear edge which most closely approaches the shaft axis at a first distance as measured on a first line which is perpendicular to the first linear edge and which passes through the shaft axis;

a second linear edge which is perpendicular to the first linear edge, wherein the second linear edge most closely approaches the shaft axis at the first distance as measured on a second line which is perpendicular to the second linear edge and which passes through the shaft axis;

a rounded segment connecting the first edge and the second edge, wherein the rounded segment most closely approaches the shaft axis at a second distance as measured on a third line which is perpendicular to the rounded segment and which passes through the shaft axis, wherein the second distance is greater than the first distance;

wherein the first lineal edge and second lineal edge, if extended, would meet at an intersection point outside of the face, and wherein the intersection point is spaced apart from the shaft axis by a third distance;

wherein the second distance is approximately one half of the sum of the first distance plus the third distance.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 8,779,760 B2
APPLICATION NO. : 13/156735
DATED : July 15, 2014
INVENTOR(S) : James William Sterling

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Claims:

Please delete claim 3 located in column 6, line 66.

Column 7, claim 4, line 4; please replace "system of claim 3" with --system of claim 1--.

Column 7, claim 8, lines 27-28; please replace "an arrangement Magnetoresistive Resistive sensors" with --an arrangement of Magnetoresistive sensors--.

Column 8, claim 15, line 13; please replace "Magnetoresistive Resistive (MR) sensors" with --Magnetoresistive (MR) sensors--.

Signed and Sealed this
Sixteenth Day of September, 2014

Michelle K. Lee
Deputy Director of the United States Patent and Trademark Office

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

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On the title page, under abstract “18 Claims, 5 Drawing Sheets” should read --17 Claims, 5 Drawing Sheets--.

In the Claims:

Please delete claim 3 located in Columns 6-7, lines 66-3.

Column 7, claim 4, line 4; please replace “system of claim 3” with --system of claim 1--.

Column 7, claim 8, lines 27-28; please replace “an arrangement Magnetoresistive Resistive sensors” with --an arrangement of Magnetoresistive sensors--.

Column 8, claim 15, line 13; please replace “Magnetoresistive Resistive (MR) sensors” with --Magnetoresistive (MR) sensors--.

This certificate supersedes the Certificate of Correction issued September 16, 2014.

Signed and Sealed this
Fourteenth Day of October, 2014

Michelle K. Lee

Michelle K. Lee
Deputy Director of the United States Patent and Trademark Office